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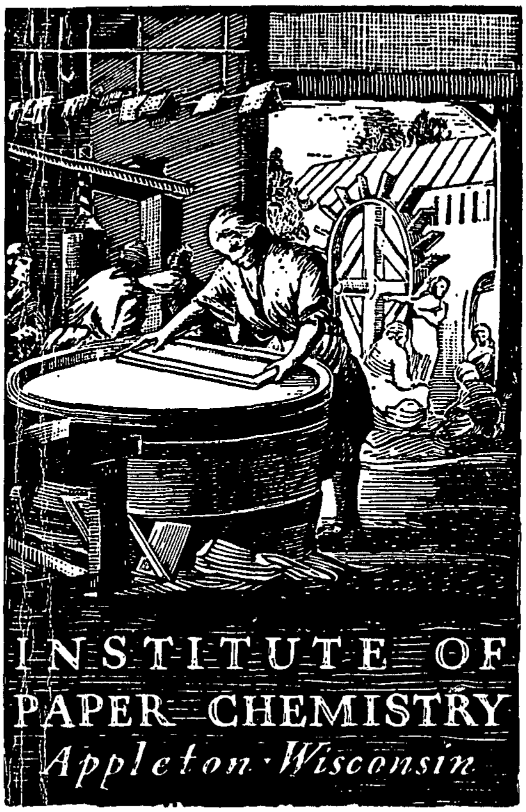

RELATIONSHIPS BETWEEN COMBINED BOARD SCORELINE CRACKING AND LINERBOARD PROPERTIES

Project 2695-17

Report One

A Summary Report

to

FOURDRINIER KRAFT BOARD INSTITUTE, INC.

December 27, 1974

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THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

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TABLE OF CONTENTS

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SUMMARY

This study was initiated for the purpose of investigating relationships between combined board scoreline cracking at the body (panel) scorelines and the tensile, plybond, and transverse shear characteristics of linerboard.

When combined board is folded along the body scoreline, high MD tensile stresses and strains are induced in the outer fiber layers of the double-face liner. The magnitude of these strains will be dependent somewhat on the amount of transverse shear deformation which occurs. The transverse shear deformations involve strains in the MD – thickness plane (designated $\underline{xz}$ plane) of the linerboard. In general, greater amounts of shear deformation will tend to reduce the magnitude of the tension stresses in the outside surface of the double-face liner and hence reduce the tendency to crack. As the tensile stresses and strains induced in the double-face liner approach and equal the limiting strength of the double-face liner, cracking may be expected to occur.

For this study commercial samples of 69- and 90-lb linerboard were double-faced to "standard" single-faced board and scored. The boards were then folded at 15- and 50% RH to determine their degree of cracking in the two atmospheres. The combined board scoreline cracking was then correlated with various linerboard properties. The following results were obtained.

1. The five properties or material factors exhibiting statistically significant correlations with combined

board cracking at the 0.01 level at both RH conditions are listed below in decreasing order of correlation at 50% RH.

a. Shear stiffness-to-stretch ratio ($G_{xz}t/S$).

b. Shear stiffness ($G_{xz}t$).

c. Tensile strength.

d. Tensile stiffness ($E_{x}t$).

e. Shear stiffness-to-tensile stiffness ratio ($G_{xz}t/E_{x}t$).

Within the proportional limit, the maximum bending stress induced in the double-face liner should be dependent on both the tensile and shear moduli or stiffnesses of the linerboard. Assuming the same considerations qualitatively apply at the high stress levels associated with cracking would account in part for the significant correlations obtained with these properties. The above suggests that any manufacturing technique which increases the tensile and shear stiffnesses such as increased bonding, surface and ~~stretch~~ treatment, addition of STIFFENING AGENTS ~~hardener~~, etc., would increase the tendency of the linerboard to crack at the scoreline when folded at a given moisture content. Decreasing the moisture content at the time of folding will intensify the adverse effect whereas increasing the moisture content will reduce the cracking tendency.

2. Cracking tended to increase as either the shear or tensile stiffness increased as would be expected on the basis of approximate theoretical considerations. In general, increasing the fiber-to-fiber bonding within the normal range should increase the tensile stiffness and, if accompanied by increases

in shear stiffness, would have the effect of increasing the cracking proclivity of the linerboard.

3. The transverse shear modulus values were much lower in magnitude than the tensile modulus values. For example, at 50% RH the average ratios of tensile-to-shear moduli were 372 and 228 for 69- and 90-lb linerboard, respectively. For comparison purposes the corresponding ratio for steel is about 2.5. Thus, because of its low shear modulus, shear effects in bending and folding would be expected to be of greater importance for linerboard than for conventional structural materials.

4. While the correlations were highly significant in a statistical sense, the relationships exhibited considerable scatter and some questions arose relative to basis weight effects due to the nature of the data. It appears that future work should be directed toward (a) developing a better theoretical understanding of the stresses induced during folding, and (b) the development of better methods for evaluating the pertinent properties. For example, while the present work supports the importance of shear properties, the methods used to evaluate them were subject to considerable variability and may not have provided very accurate and precise estimates of either the modulus or maximum shear properties.

One desirable approach would involve determination of the magnitude of the strain induced in the outer fiber layer of the double-face liner at time of cracking in relation to material properties, moisture content at time of folding and scoring conditions. It is believed this could be accomplished by employing special graphite strain gages. Direct comparison of the maximum strain values at cracking with stretch values determined in various ways would be quite enlightening. It also appears that future work should give more consideration to material variability, inelastic tensile properties, compressive stress-strain properties as they may affect the tensile strains induced in the double-face liner, and RH effects.

INTRODUCTION

A recurrent problem in the manufacture and use of corrugated boxes is rupture or cracking of the double-face liner along the score when the board is folded or subsequently stored in a very dry atmosphere after folding. It is usually a seasonal problem with most difficulties being encountered during winter when inside humidities drop to low levels. Cracking is usually most severe for vertical (body) scorelines where the score is oriented at 90° to the machine direction of the liner because the strains set-up during folding coincide with the direction of least stretch.

In general, more cracking problems are encountered when the combined board is fabricated with heavyweight double-face liners – i.e., 69- and 90-lb liner. This is a result of the fact that the bending strains set up in the outer layers of the folded double-face liner are directly proportional to the thickness of the double-face liner for a given radius of curvature. Thus, higher bending strains will be induced in the extreme fiber layer of the thicker linerboards and cracking is more likely to occur.

With the foregoing in mind, this study was initiated for the purpose of investigating relationships between combined board scoreline cracking (body scores) and the plybond, transverse shear, and tensile characteristics of linerboard.

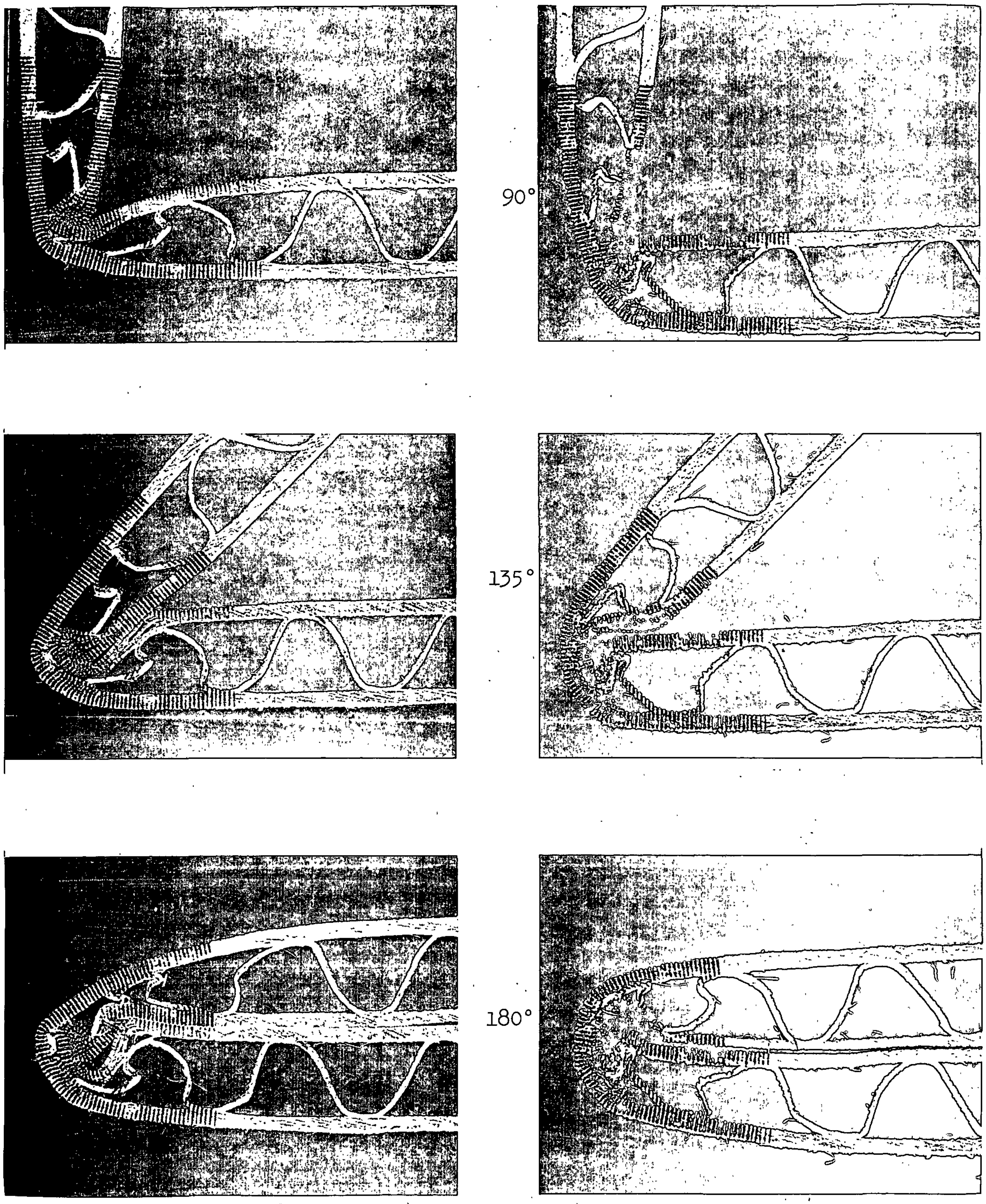
BACKGROUND CONSIDERATIONS

When combined board is folded along a scoreline, the inside liner buckles inward and then is folded back on itself in the early stages. By the time the board has been folded about 135° the inside liner forms an anvil about which the double-face liner is stretched and bent (Fig. 1). Thus, an impasse is reached because the double-face liner is prevented from freely displacing inwardly by the single-face liner. As one result, the torque required to fold the board rapidly increases as the board is folded beyond 135°F and the single-face liner is distorted sufficiently to permit completion of the fold. As the stresses and strains induced in the double-face liner approach and equal the limiting "strength" of the double-face liner during the folding process, cracking may be expected to occur.

During folding the significant types of stress and strain induced in the double-face liner are believed to be as follows:

1. Bending,
2. Shear,
3. Direct (uniform across thickness) tension.

It is believed that direct tensile strains which are approximately uniform across the thickness of the double-face liner are induced due to (a) the resistance of the "folded" inner facing to compression buckling and distortion, and (b) the resistance of the medium to "flat crush" stresses. These tensile strains would be expected to add to the bending strains induced in the outside liner and which are discussed below.



Specimen 1

Specimen 2

Figure 1. Stages in Combined Board Folding — About 3X Magnification

The bending strains are induced by the bending of the outer facing (double-face liner) about the "anvil" made by the single-face liner. The maximum tensile stress and strain due to bending occurs on the outside surface of the fold. Thus, the tensile stresses and strains due to bending are of major importance in determining whether cracking will occur. Within the elastic limit and neglecting shear effects, the maximum tensile stress and strain on the outside surface of the fold may be expressed as follows (1,2):

$$S = Mc/I = E_x t/2\ R_b \tag{1}$$

$$\varepsilon = t/2\ R_b \tag{2}$$

where
- S = maximum tensile stress in outer layer
- ε = maximum tensile strain in outer layer
- M = bending moment
- c = distance from neutral axis to outer fiber layer (assumed equal to one-half the liner caliper)
- t = liner caliper
- E = tensile modulus
- R_b = radius of curvature due to bending
- $E_x t$ = tensile stiffness

Thus, for a given curvature, the induced tensile stress will be directly proportional to the tensile stiffness of the linerboard and the induced strain is proportional to the thickness.

Above the proportional limit, Equations (1) and (2) are no longer appropriate because the unit stresses are not directly proportional to the strains and, hence, are not proportional to the distance from the neutral axis (3). Also, if the tensile and compression properties are different, the neutral axis will shift away from the side where the fibers exhibit the greatest strain. This is likely to be a factor in the case of linerboard because the ultimate strengths in tension and compression are different. Therefore, Equations (1) and (2) cannot be expected to hold exactly at the high stress levels associated with cracking but they do provide qualitative insight into the properties involved.

The derivation of Equations (1) and (2) neglects shear deflection and deformation. Beam deflections due to shear are usually of negligible importance where (a) the beam span is long relative to the thickness, and (b) the shear modulus (G) is not materially different in magnitude from the tension and compression moduli (E). For example, in Reference (3) it is noted that "in wood beams, because of the small value of G compared to E, deflection due to shear is much more important." This consideration seems to apply in the case of linerboard also inasmuch as the test data in a later part of the report show that the ratios of the tensile (E_x) to transverse modulus (G_{xz}) averaged about 345 and 245 for 69- and 90-lb liners, respectively. For comparison purposes, steel exhibits a ratio of about 2.5 — about 100-150 times smaller than in the case of linerboard. Also considered as a beam, the effective span length of the folded and bent outside liner is relatively small which would also appear to indicate that shear effects may be of importance. Some shear distortion appears to be present at the apex of the folded region shown in Fig. 2.

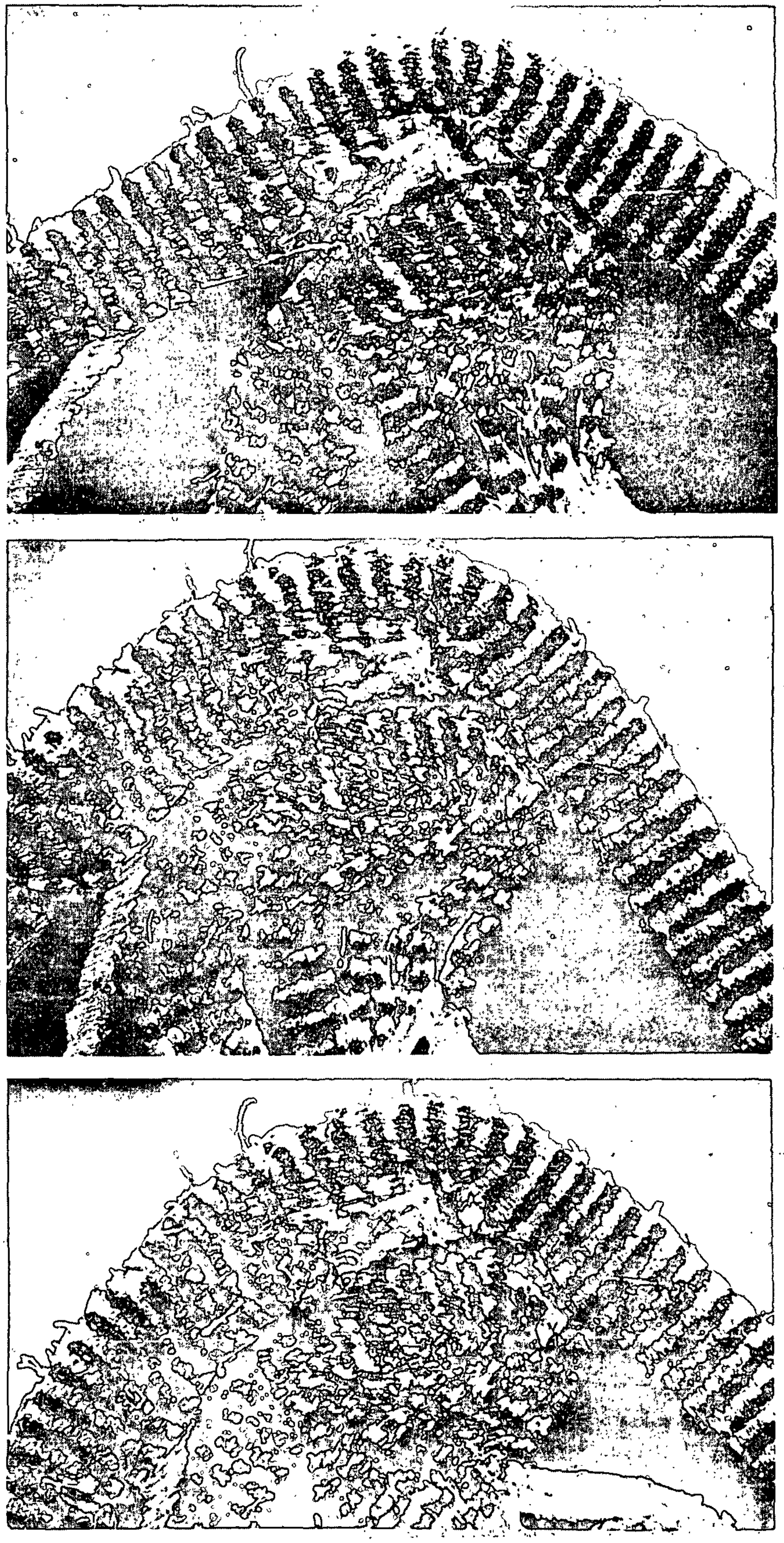
For a beam of uniform cross section, the total deflection is the sum of the deflection due to bending and shear deformation — i.e.:

$$Y_t = Y_b + Y_s \qquad (3)$$

where Y_t = total deflection

Y_b = deflection due to bending stresses

Y_s = deflection due to shear stresses



90°

135°

180°

Figure 2. Stages in Combined Board Folding – About 20X Magnification

The bending and shear deflections are related as follows within the proportional limit (1-3):

$$\frac{Y_s}{Y_b} = k\left(\frac{E}{G}\right)\left(\frac{t}{L}\right)^2 \quad (4)$$

where E = modulus of elasticity

G = shear modulus

t = beam thickness

L = beam span

k = constant dependent on type of beam and loading

The above equation shows that the shear deflections become of greater importance for materials having a low shear modulus relative to the modulus of elasticity and for short thick beams as mentioned previously. Substituting Equation (4) in Equation (3) gives the following:

$$Y_t = Y_b\left[1 + k\left(\frac{E}{G}\right)\left(\frac{t}{L}\right)^2\right] \quad (5)$$

or

$$Y_b = \frac{Y_t}{\left[1 + k\left(\frac{E}{G}\right)\left(\frac{t}{L}\right)^2\right]}. \quad (6)$$

Thus, for a given total deflection the deflection due to bending decreases as the shear deformation increases, i.e., as the term in brackets becomes greater.

As indicated in Reference (2) the deflections can be approximately related to curvatures (R_b and R_t) as follows:

$$Y_t \doteq L^2/8 \cdot R_t \quad (7)$$

and

$$Y_b \doteq L^2/8\ R_b. \tag{8}$$

Therefore,

$$R_b/R_t \doteq Y_t/Y_b \tag{9}$$

Thus, substituting Equations (5) and (9) in Equations (1) and (2) gives the following for the stress (S) and strain (ε) in the outer fiber layers in the elastic region:

$$S = E\ t/2\ R_t \left[1 + k\left(\frac{E}{G}\right)\left(\frac{t}{L}\right)^2\right] \tag{10}$$

or

$$\varepsilon = t/2\ R_t \left[1 + k\left(\frac{E}{G}\right)\left(\frac{t}{L}\right)^2\right]. \tag{11}$$

In the elastic region the tensile stress developed in the outer fiber layers is dependent on the tensile stiffness ($E_x t$) and a shear correction term involving the tensile and shear moduli. The higher the shear modulus, the greater the induced stress, and, hence, the greater the likelihood of cracking assuming the same considerations hold at high stress levels.

Paperboard is commonly considered an orthotropic elastic material rather than isotropic and this must be taken into account in applying the above concepts. In general, an orthotropic material is characterized by 12 material constants of which 9 are independent. They are as follows where subscripts x, y, and z refer to the MD, CD, and thickness directions, respectively:

1. Young's moduli (moduli of elasticity): E_x, E_y, E_z.
2. Poisson ratios: μ_{xy}, μ_{yx}, μ_{xz} ...
3. Shear moduli: G_{xy}, G_{xz}, G_{yz}.

The pertinent property orientations involved in vertical (body) score-line cracking are the MD Young's modulus (modulus of elasticity) E_x or stiffness E_xt and the transverse shear modulus G_{xz} or stiffness $G_{xz}t$. It should be noted that the torsion test methods used by Jones (4) and Setterholm (5) involve shear stresses in the xy plane and, hence, are not appropriate for the measurement of shear properties in the xz or yz planes.

Based on the above concepts, it appears that both the tension and shear properties of linerboard may affect combined board cracking. The shear effects are probably a secondary factor, however, because cracking essentially occurs due to a tensile failure of the double-face liner — primarily of its outside surface unless the cracking is very severe.

The previous discussion focussed attention on the properties affecting the stresses induced in the outside liner. However, failure occurs when the induced stress or strain equals or exceeds the allowable stress or strain (stretch) of the liner. From one viewpoint, emphasis should be placed on strain because the combined board is forced to fold through 180°, i.e., to essentially a constant configuration. Also, it is well known that cracking increases rapidly when the moisture constant is lowered and the stretch of the board decreases. For example, in Reference (6) the average degrees of cracking for combined boards with 69- and 90-lb double-face liners were as shown in Table I and Fig. 3.

Decreasing the RH from 50 to 10% RH increased the degree of cracking of 69-lb linerboard from 0.12 to 66% and for 90-lb linerboard from 1.6 to 92%. It appears that decreasing RH causes decreases in stretch and increases in tensile and shear stiffnesses which serve to explain in part the large increases in cracking at low RH levels.

TABLE I

EFFECT OF RH ON COMBINED BOARD CRACKING

RH, %	Combined Board Cracking, %	
	69-lb Double-face Liner	90-lb Double-face Liner
10	66	92
20	32	69
30	9	35
40	1.5	10
50	0.12	1.6

In Fig. 3 the percentage cracking vs. RH values are plotted on both linear and arithmetic probability coordinates to illustrate another aspect of cracking behavior. On linear coordinates the relationships are markedly nonlinear whereas linear relationships are obtained with the arithmetic probability coordinates and the lines for the two grades are essentially parallel. Nearly all linerboard samples exhibit similar behavior though their cracking vs. RH relationship may be displaced upward or downward from the average lines shown in the figure (5). In general, scorelines tend to "break" irregularly along their length, hence the stresses induced in the outside liner may be expected to exhibit considerable variability from location-to-location. Linerboard properties such as tensile stretch and strength also exhibit considerable variability. It may be conjectured that the degree of combined board cracking obtained under given conditions is dependent on both the variability in the folding process and material quality. Thus, the occurrence of cracking like most failure processes involves statistical considerations and this may account for the linear relationships obtained using arithmetic probability coordinates.

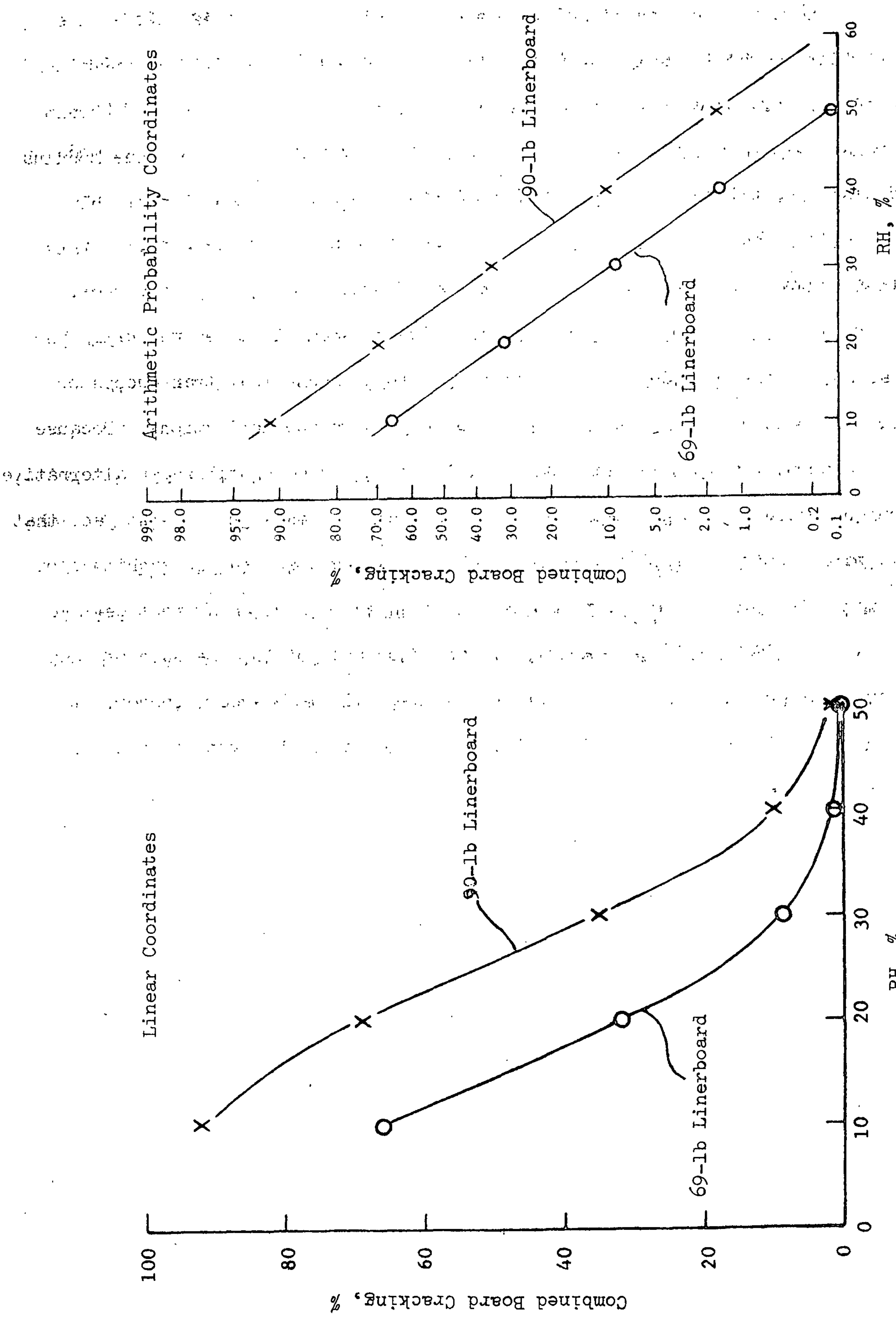


Figure 3. Percentage Cracking vs. RH Values

There are no established methods for evaluating the shear properties of linerboard — particularly in the $\underline{xz}$ plane. A complete shear load deformation curve to failure would be most desirable; however, this is difficult to obtain on a relatively thin material such as linerboard. Estimates of the shear modulus could also be obtained from 4-point beam tests. In general, the span of the beam should be chosen so that deflections due to shear are of reasonably large magnitude compared to the bending deflection in order to obtain accurate estimates of the shear modulus. The deflection due to shear involves measuring the midspan and load-point deflections. Very low force mechanical transducers or optical methods could probably be required to measure the deflections. Because of the instrumentation problems involved, it was decided to utilize an alternative technique based on 3-point beam tests. This technique makes use of the fact that the apparent stiffness ($\underline{EI}$) increases with increasing span and the magnitude of the change is related to $\underline{G}_{\underline{xz}}$. In addition, a punch type of shear test devised for plastics (ASTM D732) was employed in an effort to obtain a measure of shear strength. Both approaches were believed to have disadvantages; however, it appeared that they would provide an initial estimate of the importance of the shear properties.

MATERIALS

Ten 69- and eleven 90-lb commercial samples of unbleached kraft linerboard were obtained for the study as shown in Table II.

TABLE II

LINERBOARD SAMPLES

Company Code	Sample Number 69-lb	Sample Number 90-lb
A	744	743
B	745	753
C	746	747
D	748	--
E	749	750
F	751	752
G	754	755
H	757	758
I	759	760
J	761	762
K	--	764
L	--	756

COMBINED BOARD CRACKING EVALUATION

In order to evaluate the cracking proclivities of the samples, each sample was double-faced to "standard" A-flute single-faced board. For the boards made with the 69-lb double-face liners, the single-faced board was made with a 69-lb single-face liner and 26-lb medium. For the boards made with the 90-lb double-face liners, the single-faced board was made up with a 90-lb single-face liner and 26-lb medium. Starch adhesive was used. Ten sheets approximately 12 x 18 inches in size were prepared for each double-face liner sample.

Each sheet was scored on a rotary slitter-scorer using a body-type score profile of the V-male vs. flat female type. The scorelines were at right angles to the machine direction of the combined board. Two scorelines were made on each sheet. The scoring clearances were set so as to equal the sum of the liner and medium calipers plus 0.005 inch.

After scoring, each scoreline was spray-painted with flat black paint (Rust-Oleum No. 412) on the double-face liner. The purpose of the coating was to increase crack visibility and facilitate measurement of the degree of cracking after folding.

After drying the paint coating, five combined board sheets from each sample were conditioned for at least 48 hours in each of the following atmospheres:

1. 15% RH and 73°F
2. 50% RH and 73°F

After conditioning, the boards were folded along the scorelines and the degree of cracking was evaluated by measuring the cumulative length of severe cracks on the scorelines. The cracking length was divided by the total length of scoreline — about 120 inches — to place it on a percentage basis.

LINERBOARD TESTS

Each linerboard sample was evaluated for the following properties after conditioning at 15 and 50% RH and 73°F:

1. Basis weight
2. Caliper: 40 determinations in each atmosphere per sample

3. MD Tensile properties (whole sheet): 10 tests in each atmosphere
    a. Tensile strength
    b. Stretch
    c. Modulus of elasticity, $\underline{E}_{\underline{x}}$
    d. Tensile stiffness, $\underline{E}_{\underline{x}}\underline{t}$
    e. Tensile energy absorption (TEA)
4. MD Tensile properties, felt side — after grinding away most of the sheet so as to leave about a 4 mil-thick specimen on felt side (tested at 50% RH only, 4 tests per sample)
    a. Tensile strength
    b. Stretch
    c. Modulus of elasticity
    d. Tensile stiffness
    e. Tensile energy absorption
5. Properties derived from MD 3-point beam tests
    a. Shear modulus, $\underline{G}_{\underline{xz}}$
    b. Shear stiffness, $\underline{G}_{\underline{xz}}\underline{t}$
    c. Bending modulus, $\underline{E}_{\underline{xb}}$
    d. Flexural stiffness, $\underline{D}_{\underline{ax}}$
6. Plug shear (ASTM D732) — 3 tests per sample per RH level
7. $\underline{z}$-Direction tensile strength after 3 degrees of preflexing (4 tests per sample per degree of flexing)
    a. Unflexed
    b. Preflexed over a 0.188-inch mandril
    c. Preflexed over a 0.096-inch mandril

Special test procedures are described below:

1. Tensile properties on felt side.

As mentioned previously, when combined board is folded, it is believed that high tensile stresses and strains are induced in the outer liner and, in particular, in the outer fiber layer of the outer liner, i.e., on the felt side in usual practice. In the manufacture of linerboard the fibers on the felt side may be refined to a different degree and differ in other respects from those in the remainder of the sheet. Consequently, it was conjectured that measurements of the tensile properties of the fibrous layers near the felt side might be better related to cracking than the conventional tensile properties determined on the whole sheet.

To investigate this possibility, a surface grinder was used to grind away most of the sheet so as to leave about a 0.004-inch thick specimen on the felt side. Four tensile specimens from each sample were prepared in this manner and tested at 50% RH using a test span of 5 inches (as limited by the surface grinder).

2. Properties derived from 3-point beam tests.

Tests on MD 3-point beam specimens were used to calculate the shear modulus G_{xz} and shear stiffness $G_{xz}t$. The central deflection of a 3-point beam consists of two parts — one attributable to pure bending and the second to shear effects. It can be shown that the following equation describes the behavior of MD 3-point beams having a rectangular cross section (1,3).

$$D_x = D_{ax}\left[1 + \left(\frac{6}{5}\right)\left(\frac{E_x}{G_{xz}}\right)\left(\frac{t}{L}\right)^2\right] \qquad (12)$$

or

$$\frac{1}{D_{ax}} = \left(\frac{1}{D_x}\right) + \left(\frac{6}{5}\right)\left(\frac{E_x}{G_{xz}}\right)\left(\frac{t}{L}\right)^2\left(\frac{1}{D_x}\right) \qquad (13)$$

where D_x = true MD flexural stiffness

D_{ax} = apparent MD flexural stiffness neglecting shear

E_x = modulus of elasticity (MD)

G_{xz} = transverse shear modulus, xz plane

t = thickness

L = span

In Equation (13), D_x, E_x, and G_{xz} are constants for a given material; therefore, graphing $1/D_{ax}$ vs. $(t/L)^2$ results in a straight line with an intercept equal to $1/D_x$ and slope equal to $(6/5)(E_x/G_{xz})(1/D_x)$. As a result, if beams are tested at two or more span lengths, the shear modulus G_{xz} can be calculated from the slope and intercept by substituting the tensile modulus for E_x.

For this study, MD beams were tested for each sample at span lengths of 0.5, 0.75, 1.0, and 2.0 inches. Ten specimens were tested at each span length for each sample in each test atmosphere. The apparent stiffness D_{ax} was calculated at each span from the following equation:

$$D_{ax} = P\,L^3/48\,b\,y$$

where P = load on tangent line at deflection y

L = beam span

b = beam width

A least-squares analysis was then used to obtain the slope and intercept of the relationship according to Equation (13). These values together with the tensile modulus E_x were used to calculate the following properties:

1. Transverse shear modulus, G_{xz}, psi.
2. Transverse shear stiffness, $G_{xz}t$, lb/in.
3. True flexural stiffness, lb in.^{2}/in.
4. Bending modulus, E_{bx}, psi.

It should be noted that the above procedure, while relatively straightforward, is an indirect method and suffers from the fact that a relatively small effect must be distinguished by defining a straight line from a few points. However, there are no recognized procedures for evaluating the shear modulus defined above for paperboard. Recognizing its limitations, it was believed that the procedure could be used in this study to estimate the relative importance of the shear modulus and/or stiffness as regards combined board scoreline cracking.

3. Plus shear.

This test essentially involves measuring the maximum load required to force a specially hardened steel die through the thickness of the board. The apparatus and method are described in ASTM D732-46 (reapproved 1961). Three tests were carried out on each liner sample in each test atmosphere.

DISCUSSION OF RESULTS

The test results obtained at 50 and 15% RH are summarized in Tables IIIA and B, respectively. The average and median degrees of combined board cracking obtained were as follows:

	69-Lb Linerboards		90-Lb Linerboards	
	Average	Median	Average	Median
15% RH	78.0	82.6	97.9	99.6
50% RH	7.0	2.2	16.4	7.8

As would be expected, the 69-lb linerboards exhibited relatively small degrees of cracking at 50% RH. The median value was only 2.2% and only two samples exhibited percentage cracking values greater than 8.1%. At the other extreme, the 90-lb linerboards at 15% RH exhibited nearly complete cracking over the entire score length as shown by the median value of 99.6%. Considering the variability involved in the cracking evaluation and the very low and high degrees of cracking for these segments of the data, it appeared that separate correlations for these segments of the data would not be meaningful. Also, the very high degrees of cracking generally shown by the 90-lb samples at 15% RH (and to a lesser extent by the 69-lb liners) were so far above the range of commercial acceptability that any correlations would be of only limited value. For these reasons it was decided to correlate the 15 and 50% RH data separately — placing greatest emphasis on the 50% RH results.

The RH levels employed were a compromise between the desired conditions for the 69- and 90-lb linerboards. It was not anticipated that the 69-lb linerboards would exhibit such a small range of cracking at 50% RH and similarly the 90-lb linerboards at 15% RH. The employment of intermediate RH levels

TABLE IIIA

TEST RESULTS AT 50% RH AND 73°F

Sample No.	Combined Board Cracking, %	Basis Weight, lb/M ft^2	Caliper, pt.	App. Density, lb/pt.	Plug Shear, psi	Shear Modulus, (G_{xz}), psi	Shear Stiffness ($G_{xz}t$) lb/in.	Flexural Stiffness, lb-in.	Bending Modulus, psi (x 10^3)	Z D T, lb/in^2 Normal	Z D T, lb/in^2 0.188 in radius	Z D T, lb/in^2 0.096 in radius
							69-lb					
744	3.0	69.0	19.0	3.63	7924	1177	22.4	0.391	684	34	28	24
745	14.0	69.4	19.5	3.56	7444	3167	61.7	0.520	842	40	34	28
746	1.2	68.9	21.3	3.23	6979	2338	49.8	0.510	634	41	35	27
748	36.9	67.8	19.0	3.57	7958	3332	63.3	0.429	751	40	34	26
749	0.2	69.9	19.2	3.64	7593	546	10.5	0.542	918	30	26	25
751	8.1	67.9	20.5	3.31	6905	3141	64.4	0.437	609	50	41	36
754	1.3	67.7	20.8	3.25	6787	2030	42.2	0.512	683	44	37	32
757	1.2	69.9	20.3	3.44	7182	731	14.8	0.556	797	36	29	26
759	3.3	70.3	22.9	3.07	6439	713	16.3	0.823	823	31	24	20
761	1.0	67.8	21.3	3.18	6740	3128	66.6	0.548	681	58	50	43
Av.	7.0	68.9	20.38	3.39	7195	2030	41.20	0.5268	742	40.4	33.8	28.7
Max.	36.9	70.3	22.9	3.64	7958	3332	66.6	0.823	918	58	50	43
Min.	0.2	67.7	19.0	3.07	6439	546	10.5	0.391	609	30	24	20
							90-lb					
743	3.1	89.7	25.1	3.57	6873	1790	44.9	0.792	601	33	26	22
747	7.0	91.5	25.6	3.57	6658	1967	50.4	1.142	817	50	41	35
750	15.1	90.7	25.4	3.57	7118	2439	62.0	0.768	562	40	34	29
752	28.6	95.4	27.9	3.42	6191	4247	118.5	1.026	567	47	36	15
753	37.1	90.6	24.6	3.68	7621	4624	113.8	0.878	708	46	32	18
755	2.7	89.0	25.4	3.50	7632	2173	55.2	1.056	773	32	24	18
756	4.6	90.7	26.9	3.37	7054	2078	55.9	0.903	557	32	24	16
758	24.2	87.4	24.3	3.60	7139	5821	141.4	0.722	604	51	44	30
760	46.7	91.3	25.8	3.54	7477	3019	77.9	0.987	690	42	34	30
762	3.1	92.0	26.6	3.46	7312	2389	63.6	0.998	636	42	32	19
764	7.8	88.2	26.9	3.28	7064	742	20.0	0.996	614	32	23	21
Av.	16.4	90.6	25.86	3.51	7103	2844	73.05	0.9334	648	40.6	31.8	23.0
Max.	46.7	95.4	27.9	3.68	7632	5821	141.4	1.142	817	51	44	35
Min.	2.7	87.4	24.3	3.28	6191	742	20.0	0.722	557	32	23	15

TABLE IIIA (Continued)

TEST RESULTS AT 50% RH AND 73°F

Sample No.	Combined Board Cracking	Tensile Properties: Load, lb/in. Whole Sheet	Load, lb/in. Felt Side	Stretch, % Whole Sheet	Stretch, % Felt Side	TEA, ft lb/ft^2 Whole Sheet	TEA, ft lb/ft^2 Felt Side	Stiffness, E·t, lb/in. Whole Sheet	Stiffness, E·t, lb/in. Felt Side	Modulus, E, lb/in^2 (x 10^3) Whole Sheet	Modulus, E, lb/in^2 (x 10^3) Felt Side
					69-lb						
744	3.0	122	18.3	1.77	1.10	15.8	1.61	12,400	2680	653	638
745	14.0	130	27.6	1.19	1.14	11.8	2.33	17,300	3410	887	793
746	1.2	117	19.7	1.36	0.85	12.3	1.30	15,300	3190	718	742
748	36.9	133	19.9	1.65	1.06	16.8	1.60	14,500	2800	763	636
749	0.2	110	31.7	1.44	1.31	13.4	3.24	13,400	4210	698	979
751	8.1	107	19.2	1.33	0.93	11.2	1.36	13,800	3110	673	740
754	1.3	126	30.4	1.58	1.35	15.0	3.18	14,200	3560	683	890
757	1.2	107	23.8	1.57	1.24	12.6	2.23	11,900	3080	586	700
759	3.3	108	25.1	1.04	0.95	8.2	1.74	14,700	3630	642	844
761	1.0	129	19.9	1.65	0.95	16.2	1.49	14,900	3330	700	774
Av.	7.0	118.9	23.56	1.458	1.088	13.33	2.01	14,200	3300	700	774
Max.	36.9	133	31.7	1.77	1.35	16.8	3.24	17,300	4210	887	979
Min.	0.1	107	18.3	1.04	.85	8.2	1.30	11,900	2680	586	636
					90-lb						
743	3.1	131	20.2	1.44	0.82	14.3	1.41	15,900	3530	633	784
747	7.0	159	28.2	1.45	0.94	18.5	1.96	20,100	4020	785	957
750	15.1	132	13.9	1.60	0.82	15.9	1.08	15,300	2990	602	636
752	28.6	143	23.7	1.38	1.29	15.3	2.41	18,800	3050	674	663
753	37.1	176	21.0	1.53	1.10	19.7	1.72	19,900	2800	809	609
755	2.7	143	22.7	1.40	0.96	14.6	1.70	17,400	3710	685	843
756	4.6	126	15.2	1.25	0.97	11.5	1.15	15,500	2360	576	590
758	24.2	183	25.0	2.17	1.59	31.3	3.11	19,300	2760	794	690
760	46.7	176	34.2	1.38	1.12	17.6	2.89	21,500	4510	833	1002
762	3.1	147	13.5	1.77	0.78	19.6	0.91	15,900	2800	598	667
764	7.8	152	24.9	1.34	0.93	17.2	1.77	18,400	3920	684	891
Av.	16.4	151.6	22.05	1.519	1.029	17.77	1.828	18,000	3314	698	757
Max.	46.7	183	34.2	2.17	1.59	31.3	3.11	21,500	4510	833	1002
Min.	2.7	126	13.5	1.25	.78	11.5	0.91	15,300	2360	576	590

TABLE IIIB (Continued)

TEST RESULTS AT 15% RH AND 73°F

Sample No.	Combined Board Cracking, %	Basis Weight, lb/M ft²	Caliper, pt.	App. Density, lb/pt.	Plug Shear, psi	Shear Modulus, (G_{xz}), psi	Shear Stiffness, ($G_{xz}t$) lb/in.	Flexural Stiffness, lb-in.	Bending Modulus, psi ($x 10^3$)	Z.D.T., psi Unflexed	Z.D.T., psi Flexed to 0.188 in.	Z.D.T., psi Flexed to 0.096 in.
						69-1b						
744	76.2	67.0	18.6	3.60	7353	1480	27.5	0.451	841	38	29	23
745	96.0	66.2	18.6	3.56	7376	3883	72.2	0.495	923	44	35	24
746	58.8	66.1	20.4	3.24	5861	1725	35.2	0.588	831	48	38	23
748	95.1	66.0	18.4	3.59	7433	3680	67.7	0.469	903	45	36	22
749	47.5	67.9	18.7	3.63	7248	774	14.5	0.639	1173	37	28	23
751	70.7	66.0	19.4	3.40	5691	2938	57.0	0.464	763	53	42	33
754	86.4	65.5	20.0	3.28	6287	2431	48.6	0.561	841	47	38	30
757	79.5	67.7	19.9	3.40	7142	887	17.6	0.628	956	40	30	24
759	84.8	68.3	22.1	3.09	5970	1002	22.1	0.838	931	34	25	18
761	84.7	64.7	20.2	3.20	6320	4534	91.6	0.576	838	60	50	32
Av.	78.0	66.5	19.63	3.40	6668	2333	45.4	0.5709	900	44.6	35.1	25.2
Max.	96.0	68.3	22.1	3.63	7433	4534	91.6	0.838	1173	60	50	33
Min.	47.5	64.7	18.4	3.09	5691	774	14.5	0.451	763	34	25	18
						90-1b						
743	97.1	86.8	24.1	3.60	6667	1629	39.3	0.879	754	36	26	20
747	99.6	88.1	24.8	3.55	6728	4397	109.0	1.125	885	60	46	22
750	100.0	87.9	25.0	3.52	6660	3277	81.9	0.787	604	43	35	25
752	100.0	92.2	26.8	3.44	5937	4508	120.8	1.151	718	52	38	14
753	100.0	88.2	23.9	3.69	7405	5521	132.0	0.954	839	48	32	14
755	98.0	85.8	24.3	3.53	7366	3799	92.3	0.907	759	36	25	12
756	92.3	86.8	25.1	3.22	6679	2722	68.3	0.892	677	36	26	11
758	100.0	84.3	23.6	3.57	7601	5281	124.6	0.750	685	57	44	22
760	100.0	88.2	25.4	3.47	6890	3950	100.3	1.280	937	48	34	23
762	92.5	89.5	26.0	3.44	6749	3291	85.6	1.077	735	45	32	12
764	97.6	85.6	26.2	3.27	6390	1639	42.9	1.550	1034	35	23	17
Av.	97.9	87.6	25.02	3.48	6825	3638	90.6	1.0320	784	45.1	32.8	17.5
Max.	100.0	92.2	26.8	3.60	7601	5521	132.0	1.550	1034	60	46	25
Min.	92.3	84.3	23.6	3.22	5937	1629	39.3	0.750	604	35	23	11

TABLE IIIB (Continued)

TEST RESULTS AT 15% RH AND 73°F

Sample No.	Combined Board Cracking, %	Tensile Strength, lb/in.	Stretch, %	TEA, ft lb/ft^2	Tensile Stiffness, ($E_x t$), lb/in.	Tensile Modulus, (E), psi (x 10^3)
			69-lb			
744	76.2	140	1.24	12.9	16,500	887
745	96.0	133	0.90	8.4	19,000	1022
746	58.8	131	1.07	10.0	17,800	873
748	95.1	154	1.28	13.9	17,800	967
749	47.5	138	1.12	11.2	17,200	920
751	70.7	128	1.25	11.7	15,100	778
754	86.4	148	1.48	16.1	15,500	775
757	79.5	120	1.11	9.7	15,100	759
759	84.8	128	0.96	8.8	16,900	756
761	84.7	151	1.20	13.0	19,000	941
Av.	78.0	137.1	1.161	11.57	17,000	868
Max.	96.0	154	1.48	16.1	19,000	1022
Min.	47.5	120	.90	8.4	15,100	756
			90-lb			
743	97.1	148	1.07	11.6	19,800	822
747	99.6	179	1.21	15.6	21,600	871
750	100.0	164	1.39	16.6	18,000	720
752	100.0	163	1.20	14.1	20,100	750
753	100.0	203	1.22	17.4	23,800	996
755	98.0	168	1.19	14.2	20,500	844
756	92.3	142	1.08	11.4	19,100	761
758	100.0	219	1.63	27.6	21,200	796
760	100.0	206	1.09	15.5	24,200	953
762	92.5	172	1.35	17.3	19,400	746
764	97.6	174	0.93	11.4	22,700	866
Av.	97.9	176.2	1.215	15.70	20,900	830
Max.	100.0	219	1.39	27.6	24,200	996
Min.	92.3	142	0.93	11.4	18,000	720

would have provided a better opportunity for studying relationships between cracking and material properties. However, because of material and budget limitations, it was not possible to expand the study to include intermediate RH levels.

TABLE IV

COMPARISON OF AVERAGE TENSILE AND SHEAR MODULI

Grade Weight	RH, %	MD Tensile Modulus, psi (E_x)	Transverse Shear Modulus, psi (G_{xz})	Ratio E_x/G_{xz}
69	15	868,000	2333	372
	50	700,000	2030	345
90	15	830,000	3638	228
	50	698,000	2844	245

Table IV compares the average MD tensile modulus (E_x) and transverse shear modulus (G_{xz}) results. As may be noted, the shear modulus values were much lower in magnitude than the tensile modulus values. For example, at 50% RH the average ratios of tensile to shear moduli were 372 and 228 for 69- and 90-lb linerboard, respectively. For comparison purposes the corresponding ratio for steel is about 2.5. Because of the low shear modulus, shear effects in bending and folding would be expected to be of greater importance in the case of linerboard than in the case of conventional structural materials such as steel.

It also may be noted that on the average the 90-lb linerboards exhibited somewhat higher shear moduli than the 69-lb linerboards. It is believed this would tend to increase the cracking proclivity of 90-lb board over and above that which would be expected due to the higher caliper and stiffness of 90-lb board.

As another point of interest, the differences in shear modulus between grades were not related to the internal bonding measured in terms of the ZDT test which were about the same for the two grades. Thus, it appears that the transverse shear properties are not necessarily related to bonding strength as measured by z-direction tensile tests.

The correlation of the various linerboard properties with combined board cracking at 15 and 50% RH is shown in Table V. The linear correlation coefficients are shown together with coefficients obtained after transforming the percentage combined board cracking values to (a) logarithms, and (b) arithmetic probability scale values. This involves transforming the percentage cracking values to "standard deviation units" using tabulated values of the area under the normal distribution curve as discussed in Reference (6) (p. 23). The latter transformation was employed, in part, because percentage cracking *vs.* RH values are approximately linear on this scale (see Fig. 3).

It may be noted that generally the same properties exhibit statistical significance in the three ways of correlating the data although higher coefficients were generally obtained when combined board cracking in percent was transformed to the probability scale. The five properties exhibiting statistically significant coefficients at the 0.01 level at both RH conditions are illustrated in Fig. 4 and are listed below in decreasing order of correlation at 50% RH (coefficients for probability scale are shown).

1. Shear stiffness/stretch ($G_{xz}t/S$)
    a. 50% RH: $r = 0.725$
    b. 15% RH: $r = 0.793$

TABLE V

CORRELATION RESULTS

Property	Correlation Coefficient: Linear 15% RH	Linear 50% RH	Probability[a] 15% RH	Probability[a] 50% RH	Logarithmic[b] 15% RH	Logarithmic[b] 50% RH
1. Tensile properties (whole sheet)						
a. Tensile strength (T)	0.616[d]	0.656[d]	0.797[d]	0.674[d]	0.566[d]	0.653[d]
b. Stretch (S)	0.150	0.135	0.240	0.101	0.151	0.080
c. Tensile stiffness ($E_x t$)	0.617[d]	0.622[d]	0.751[d]	0.665[d]	0.561[d]	0.655[d]
d. TEA	0.428	0.419	0.582[c]	0.423	0.400	0.404
2. Tensile properties (felt side, 4 mils)						
a. Tensile strength	--	0.209	--	0.046	--	-0.039
b. Stretch (S_f)	--	0.286	--	0.157	--	0.081
c. Tensile stiffness $(E_x t)_f$	--	-0.013	--	-0.138	--	-0.195
d. TEA	--	0.244	--	0.066	--	-0.030
3. Caliper (t)	0.644[d]	0.215	0.713[d]	0.341	0.610[d]	0.389
4. Apparent density	0.171	0.422	0.360	0.380	0.115	0.331
5. Plug shear	0.223	0.249	0.250	0.145	0.187	0.085
6. Shear stiffness ($G_{xz} t$)	0.679[d]	0.661[d]	0.808[d]	0.696[d]	0.648[d]	0.681[d]
7. Bending modulus (E_b)	-0.453[c]	-0.133	-0.410	-0.278	-0.478[c]	-0.342
8. Flexural stiffness ($E_x I$)	0.520[c]	0.196	0.588[c]	0.286	0.478[c]	0.318
8. z-Direction tensile						
a. Unflexed	0.142	0.287	0.282	0.301	0.145	0.297
b. Flexed to 0.188-in. radius	0.026	0.201	0.129	0.195	0.038	0.184
c. Flexed to 0.096-in. radius	-0.381	-0.088	-0.357	-0.122	-0.348	-0.134
10. $(G_{xz} t)/S$	0.695[d]	0.680[d]	0.793[d]	0.725[d]	0.663[d]	0.713[d]
11. $(G_{xz} t)/S_f$	--	0.572[d]	--	0.635[d]	--	0.639[d]
12. $(E_x t)/S$	0.040	0.193	0.110	0.252	0.042	0.271
13. $G_{xz} t/E_x t$	0.641[d]	0.574[d]	0.733[d]	0.625[d]	0.621[d]	0.621[d]
14. T/S	0.035	-0.054	0.030	-0.030	0.006	-0.018
15. t/S	0.359	0.039	0.322	0.156	0.335	0.207

[a] Percentage cracking transformed to probability coordinates.

[b] Percentage cracking transformed to logarithms.

[c] Significant at 0.05 level.

[d] Significant at 0.01 level.

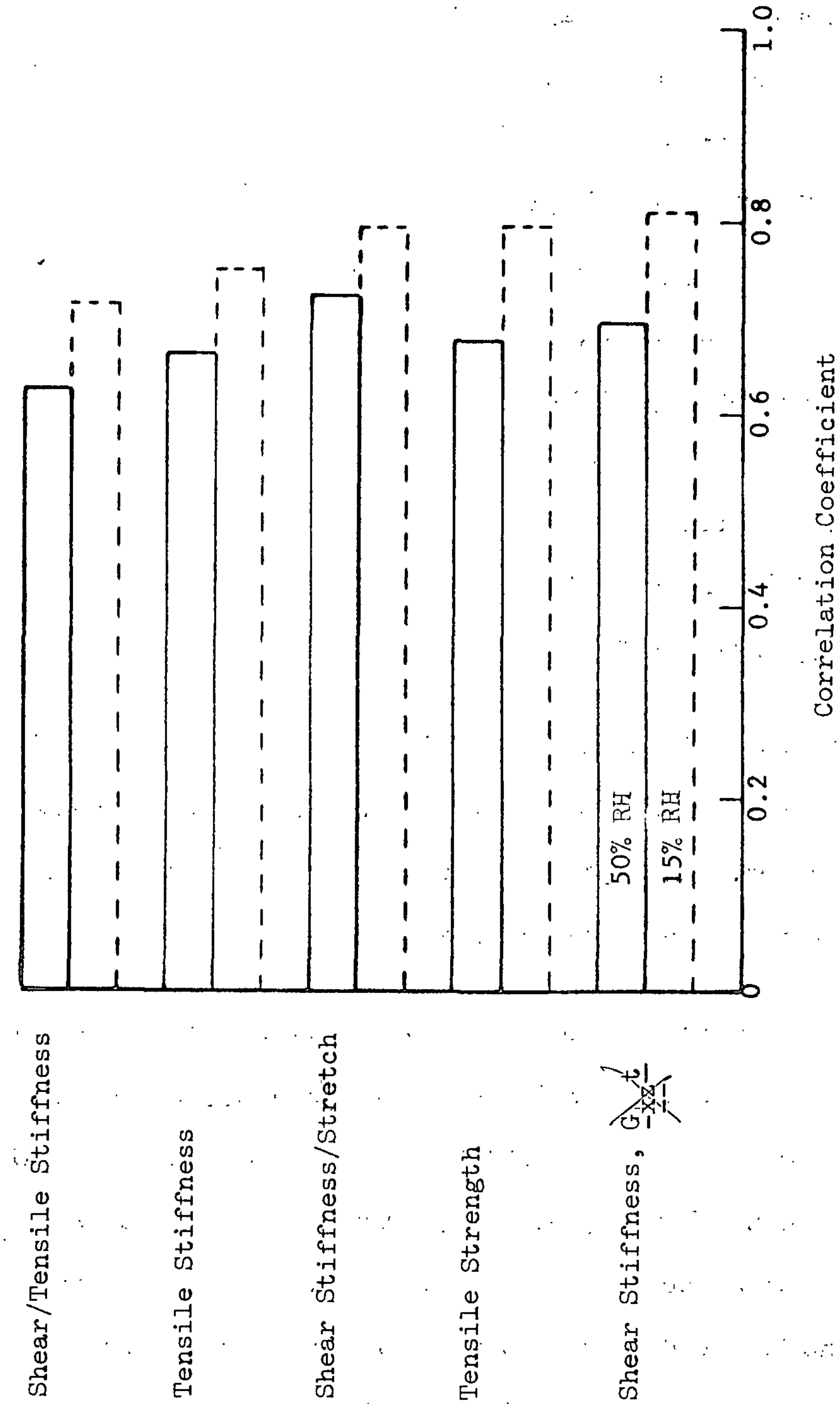


Figure 4. Five Properties that Exhibit Statistically Significant Correlation Coefficients

2. Shear stiffness ($\underline{G}_{\underline{xz}}\underline{t}$)

   a. 50% RH: $\underline{r}$ = 0.696

   b. 15% RH: $\underline{r}$ = 0.808

3. Tensile strength

   a. 50% RH: $\underline{r}$ = 0.674

   b. 15% RH: $\underline{r}$ = 0.797

4. Tensile stiffness ($\underline{E}_{\underline{x}}\underline{t}$)

   a. 50% RH: $\underline{r}$ = 0.665

   b. 15% RH: $\underline{r}$ = 0.751

5. Shear stiffness/tensile stiffness

   a. 50% RH: $\underline{r}$ = 0.625

   b. 15% RH: $\underline{r}$ = 0.733

As mentioned previously, the maximum bending stress induced on the double-face liner should be dependent on the tensile and shear moduli or stiffnesses of the liner. This probably accounts in part for the significant correlations obtained with these properties.

While the correlations were highly significant in a statistical sense, the correlations are not as high as desirable. For example, the 50% RH combined board cracking data are plotted against tensile stiffness, shear stiffness, and tensile strength in Fig. 5-7, respectively. Inspection of the graphs show that there is considerable scatter in all three relationships. It appears that future work should be directed toward (a) developing a better theoretical understanding of the stresses induced during folding, and (b) the development of better methods for evaluating the pertinent properties. For example, while the present work supports the importance of shear properties, the methods used to evaluate the shear properties were subject to considerable variability and

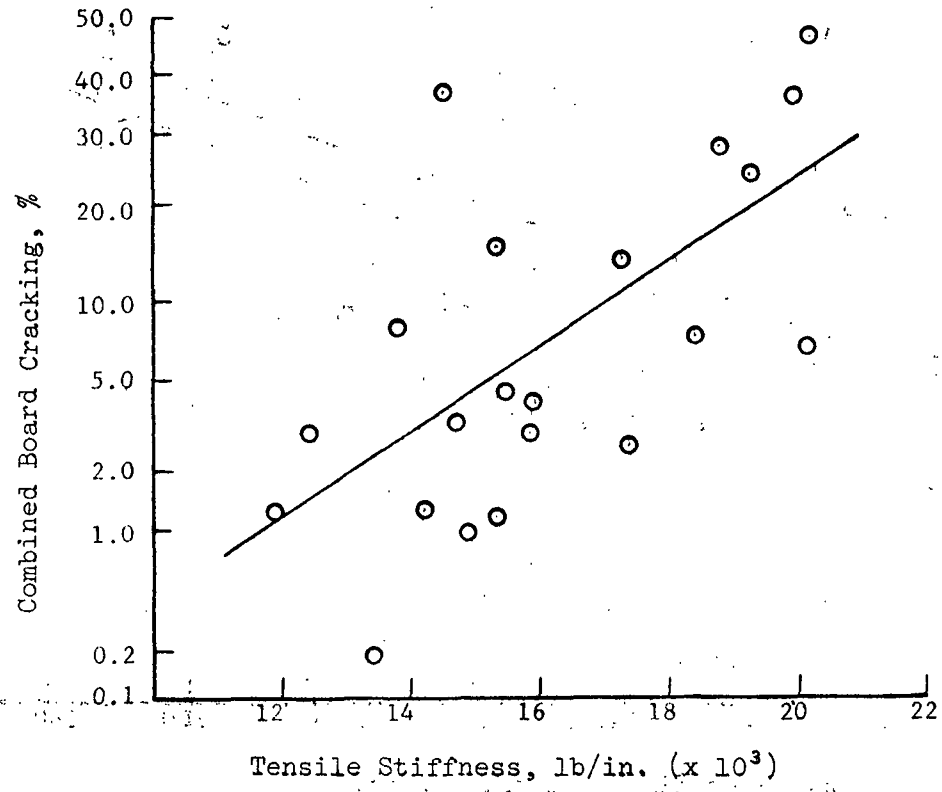


Figure 5. Combined Board Cracking *vs*. Tensile Stiffness

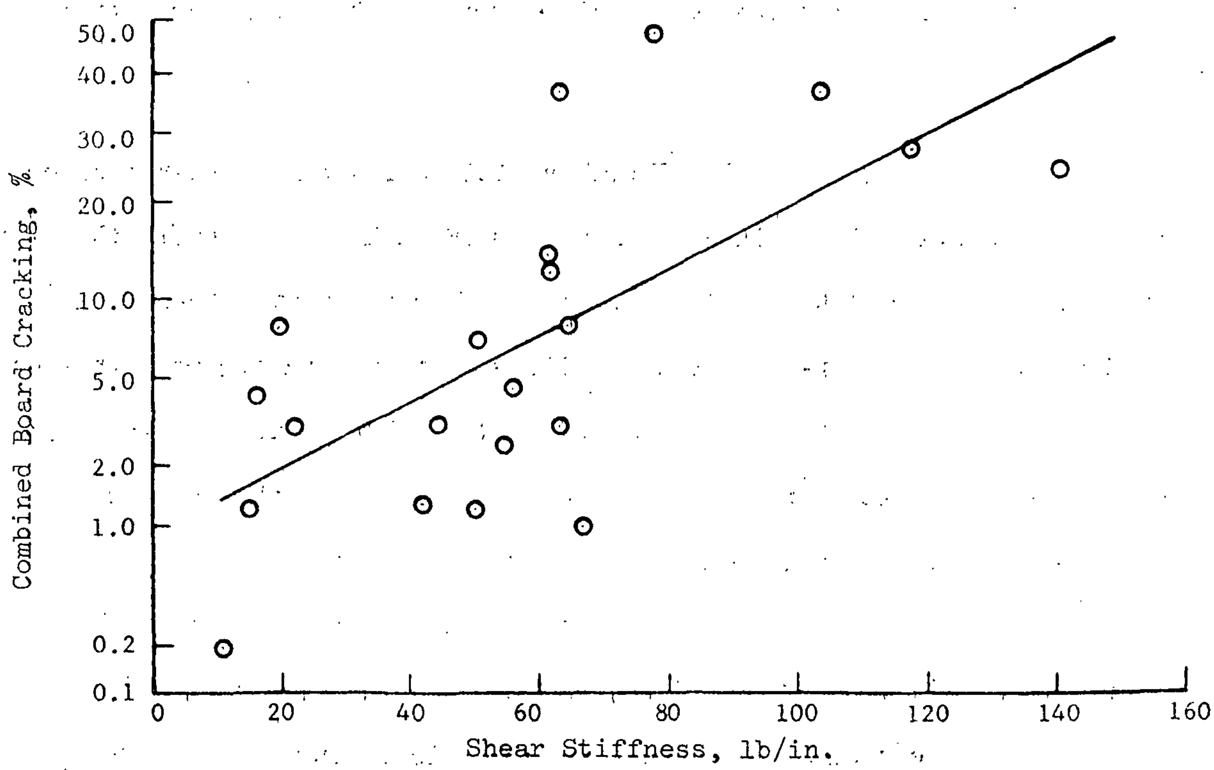


Figure 6. Combined Board Cracking *vs*. Shear Stiffness

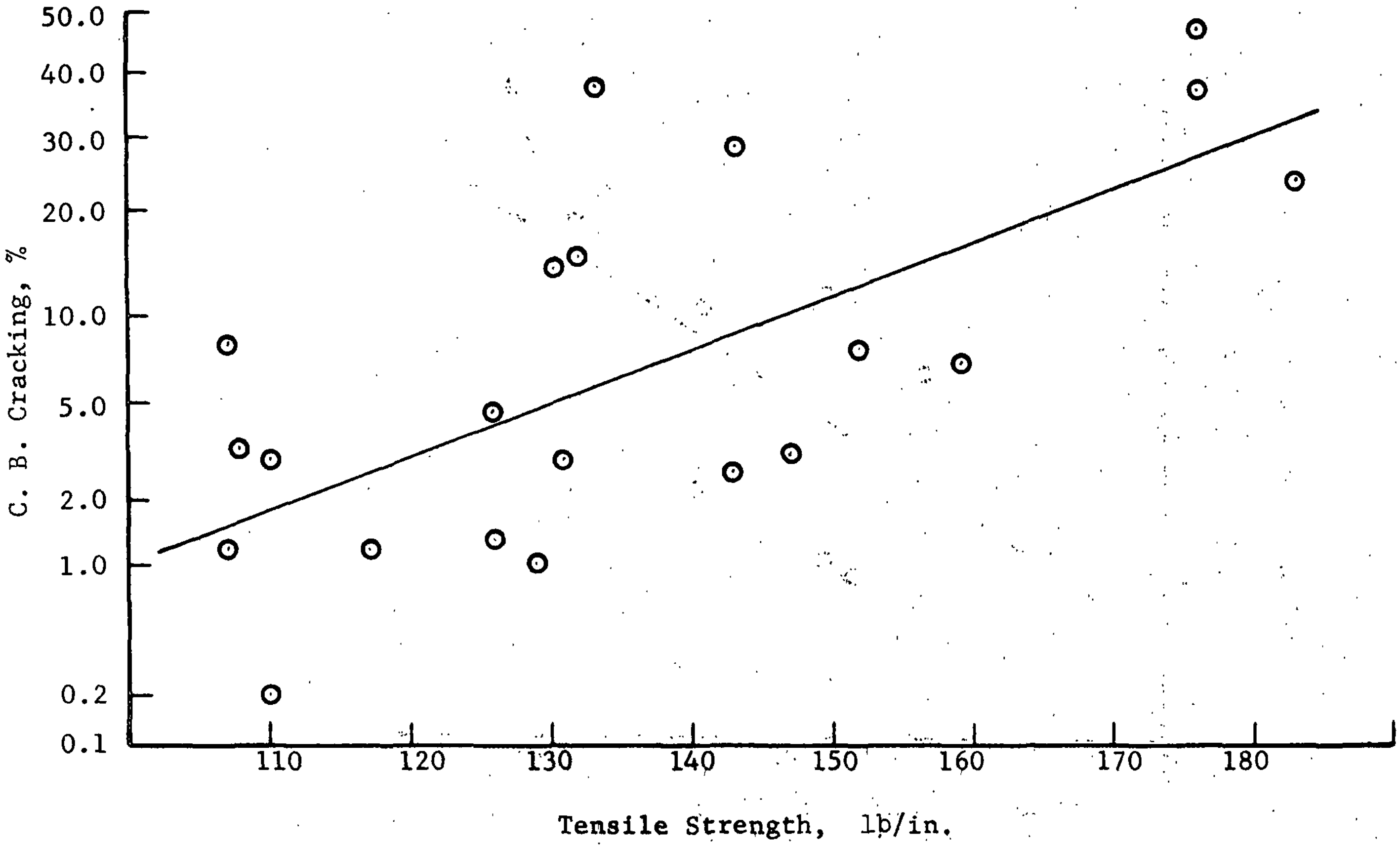


Figure 7. Combined Board Cracking vs. Tensile Strength

did not provide very satisfactory estimates of either the modulus or maximum shear strength.

The correlations in Table V were probably influenced to some extent by the inclusion of both 69- and 90-lb linerboards at each RH. However, the simple correlations by grade weight and RH in Appendix I show that the shear stiffness, shear stiffness/stretch, and shear-to-tensile stiffness ratios were significantly related to cracking at either the 0.10 or 0.05 levels (probability transformation). The magnitudes of the coefficients were in some cases about the same as shown in Table V but the lower significance levels result from the lesser degrees of freedom associated with the subdivision of the data by grade weight and RH. Thus, the shear properties seemed to be of some importance at each grade weight and RH level. The situation was less clear in the case of tensile strength and stiffness.

Both were significantly correlated with the 90-lb linerboard cracking results at 50% RH but their correlations with the 69-lb results were not high enough to be significant.

In Table V the positive coefficients for shear stiffness and the factors involving shear stiffness indicate that the higher the shear stiffness, the greater the proclivity to crack. This appears to be reasonable since increasing the shear stiffness should tend to increase the tensile stresses on the outside surface of the liner as discussed previously. The positive sign for tensile stiffness also appears to be in accord with expectations for the same reason. It appears that increasing the tensile stiffness, other factors being equal, should increase the cracking proclivity. As an extreme example, treatments with thermosetting resins which probably effect large increases in both properties generally result in brittle boards with poor bending characteristics. Unfortunately, there is little known relative to the effect of various fiber and sheet properties on shear characteristics; hence, it is not clear how the tensile and shear characteristics should be balanced to reduce cracking tendencies while retaining other necessary properties.

As mentioned previously, stretch might be expected to be one of the properties related to cracking because rupture of the double-face liner should occur when the induced strains exceed the ultimate stretch. Thus, it might be expected that stretch would exhibit negative correlations with cracking. However, the correlations with stretch in Table V were very low. In addition, the correlations involving ratios of various factors to stretch were generally no better than for the individual properties such as tensile or shear stiffness alone. The correlations by grade in Appendix I gave essentially the same results. These results were somewhat anticipated and were the reason for attempting to measure the stretch and tensile characteristics of the felt side of the sheet after grinding away all but about 4 mils of the sheet thickness. However, as may be noted in Table V, the felt side stretch values were no better related to cracking than the stretch values of the entire sheet. It appears possible that the grinding operation introduces some damage into the remainder of the sheet as the stretch values in the ground specimens were always less than the values corresponding for the whole sheet. On the average, the stretch values for the ground tensile specimens were 25 and 32% lower, respectively, than the stretch values on the whole sheet for the 69- and 90-lb boards. As a sidelight, the tensile strengths of the ground specimens were about the same as for the whole sheet when expressed in terms of stress.

A series of multiple regressions were carried out on the 50% RH data to determine if improvements could be obtained using various combinations of the properties which correlated best with combined board cracking. As in Table V, the regressions were performed using combined board cracking directly (termed linear regressions) and after transforming the cracking values to probability scale values. The results are summarized in Tables VI and VII for the linear and probability regressions, respectively.

As may be noted, only modest improvements in correlation were obtained with any of the multiple factor relationships studied. The best relationships with both factors significant were as follows:

1. No. 3B involving tensile and shear stiffness.
2. No. 8B involving the tensile stiffness and the ratio of shear-to-tensile stiffness.

TABLE VI

LINEAR MULTIPLE REGRESSIONS ON 50% RH DATA

No.	Regression Variables[a,b] Var. 1	Var. 2	Var. 3	Constant Term	Statistical Significance Var. 1	Var. 2	Var. 3	Multi. Corr. Coefficient
1A	0.00332 $E_x t$	--	--	-41.96	S.01	--	--	0.622
2A	0.274 $G_{xz} t$	--	--	-3.92	S.01	--	--	0.661
3A	0.185 $G_{xz} t$	0.00183 $E_x t$	--	-28.43	S.05	N.S.	--	0.713
4A	0.164 $G_{xz} t$	0.235 T	--	-29.61	S.10	N.S.	--	0.715
5A	0.301 $G_{xz} t$	-9.49 S	--	8.64	S.01	N.S.	--	0.678
6A	0.163 $G_{xz} t$	0.000920 $E_x t$	0.142 T	-31.78	N.S.	N.S.	N.S.	0.720
7A	0.201 $G_{xz} t$	0.00169 $E_x t$	-3.27 S	-22.29	S.10	N.S.	N.S.	0.715
8A	0.00244 $E_x t$	3024 $G_{xz} t/E_x t$	--	-38.06	S.05	S.10	--	0.704
9A	0.00126 $E_x t$	2618 $G_{xz} t/E_x t$	0.170 T	-40.66	N.S.	N.S.	N.S.	0.714
10A	0.00241 $E_x t$	3122 $G_{xz} t/E_x t$	-1.26 S	-36.01	S.05	N.S.	N.S.	0.704
11A	0.178 $G_{xz} t$	0.00307 $E_x t$	-1553 t	-12.07	S.05	S.05	N.S.	0.755
12A	0.00315 $E_x t$	0.187 ZDT	--	-46.76	S.01	N.S.	--	0.630
13A	0.339 $G_{xz} t$	-0.442 ZDT	--	10.20	S.01	N.S.	--	0.687
	Separation by Nominal Basis Weight							
14A	0.00426 $E_x t$	--	--	-53.62(69) -60.29(90)	S.01	--	--	0.644
15A	0.268 $G_{xz} t$	--	--	-4.01(69) -3.20(90)	S.01	--	--	0.662

[a] Regression form: degree of cracking, % = $a + bx_1 = cx_2$ ...

[b] Symbols are as follows:

$E_x t$ = tensile stiffness
$G_{xz} t$ = shear stiffness
T = tensile strength
t = liner caliper
ZDT = z-direction tensile strength
S = stretch

TABLE VII

MULTIPLE REGRESSIONS IN 50% RH DATA

(Degree of cracking transformed to probability scale)

No.	Regression Variables[a,b] Var. 1	Var. 2	Var. 3	Constant Term	Statistical Significance Var. 1	Var. 2	Var. 3	Multi. Corr. Coefficient
1B	0.000192 $E_x t$	--	--	-4.607	S.01	--	--	0.664
2B	0.0155 $G_{xz} t$	--	--	-2.396	S.01	--	--	0.696
3B	0.0103 $G_{xz} t$	0.000109 $E_x t$	--	-3.856	S.05	S.10	--	0.756
4B	0.00984 $G_{xz} t$	0.0123 T	--	-3.738	S.10	N.S.	--	0.744
5B	0.0175 $G_{xz} t$	-0.698 S	--	-1.471	S.01	--	--	0.724
6B	0.00972 $G_{xz} t$	0.0000859 $E_x t$	0.00359 T	-3.940	S.10	N.S.	N.S.	0.757
7B	0.0120 $G_{xz} t$	0.0000943 $E_x t$	-0.352 S	-3.194	S.05	N.S.	N.S.	0.761
8B	0.000139 $E_x t$	181 $G_{xz} t/E_x t$	--	-4.374	S.01	S.05	--	0.759
9B	0.000108 $E_x t$	170 $G_{xz} t/E_x t$	0.0045 T	-4.443	N.S.	S.10	N.S.	0.761
10B	0.000132 $E_x t$	203 $G_{xz} t/E_x t$	-0.288 S	-3.907	S.05	S.05	N.S.	0.763
11B	0.0101 $G_{xz} t$	0.000141 $E_x t$	-39.7 t	-3.437	S.05	S.10	N.S.	0.765
12B	0.000182 $E_x t$	0.0102 ZDT-N	--	-4.869	S.01	N.S.	--	0.672
13B	0.0193 $G_{xz} t$	-0.0252 ZDT-N	--	-1.591	S.01	N.S.	--	0.723
	Separation by Nominal Basis Weight							
14B	0.000207 $E_x t$	--	--	(-4.796(69) (-4.904(90)	S.01	--	--	0.667
15B	0.0139 $G_{xz} t$	--	--	(-2.422(69) (-2.196(90)	S.01	--	--	0.709

[a]Regress form: degree of cracking (probability scale) = $a + bx_1 + cx_2$ ...

[b]Symbols are as follows:

$E_x t$ = tensile stiffness
$G_{xz} t$ = shear stiffness
T = tensile strength
t = liner caliper
ZDT = z-direction tensile
S = stretch

Their multiple correlation coefficients were each about 0.76 — only slightly greater than the simple correlation coefficients of 0.664 and 0.696 obtained for tensile and shear stiffness separately.

The regression equations for 3B and 8B are shown below together with their linear counterparts (3A and 8A):

A. Cracking expressed in % (3A and 8A)

No. 3A:

$$C = 0.00183\ E_x t + 0.185\ G_{xz} t - 28.4,$$

No. 8A:

$$C = -0.00244\ E_x t + 3.024\ (G_{xz} t / E_x t) - 38.1,$$

B. Cracking transformed to probability scale values

No. 3B:

$$C_p = 0.000109\ E_x t + 0.0103\ G_{xz} t - 3.86,$$

No. 8B:

$$C_p = 0.000139\ E_x t + 180.9\ (G_{xz} t / E_x t) - 4.374,$$

where C = cracking, %

C_p = cracking, % transformed to probability scale values

$E_x t$ = tensile stiffness

$G_{xz} t$ = shear stiffness

Predictions based on regression Equations 3A and 3B are shown in Table VIII. In general, the predictions are not highly precise. However, in many cases they identify the samples which exhibited relatively large amounts of cracking.

TABLE VIII

COMPARISON OF PREDICTED AND OBSERVED CRACKING AT 50% RH

Sample No.	Combined Board Cracking, %				
	Observed	Predicted[a]	Difference	Predicted[b]	Difference
69-lb liners					
744	3.0	1.1	1.9	0.0[c]	3.0
745	14.0	9.0	5.0	14.6	- 0.6
746	1.2	4.7	- 3.5	8.8	- 7.6
748	36.9	5.2	31.7	9.8	27.1
749	0.2	1.1	- 0.9	0.0[c]	0.2
751	8.1	4.6	3.5	8.7	- 0.6
754	1.3	3.0	- 1.7	5.3	- 4.0
757	1.2	0.8	0.4	0.0[c]	1.2
759	3.3	1.8	1.5	1.5	1.8
761	1.0	6.1	- 5.1	11.1	-10.1
90-lb liners					
743	3.1	4.8	- 1.7	8.9	- 5.8
747	7.0	12.5	- 5.5	17.6	-10.6
750	15.1	6.0	9.1	11.0	4.1
752	28.6	27.8	0.8	27.9	0.7
753	37.1	30.1	- 7.0	29.0	8.1
755	2.7	8.2	- 5.5	13.6	-10.9
756	4.6	5.5	- 0.9	10.2	- 5.6
758	24.2	38.2	-14.0	33.0	- 8.8
760	46.7	23.7	23.0	25.3	21.4
762	3.1	6.9	- 3.8	12.4	- 9.3
764	7.8	5.0	2.8	8.9	- 1.1
Av.			6.1		6.8

[a] $\underline{C}_{\underline{p}} = -3.86 + 0.0103\underline{G}_{\underline{xz}}\underline{t} + 0.000109\underline{E}_{\underline{x}}\underline{t}$.

$\underline{C}_{\underline{p}}$ = Cracking % transformed to probability scale values.

[b] $\underline{C} = 0.00183\underline{E}_{\underline{x}}\underline{t} + 0.185\underline{G}_{\underline{xz}}\underline{t} - 28.4$.

$\underline{C}$ = Cracking in percent.

[c] Prediction was negative and hence was taken as 0% cracking.

A portion of the prediction error is probably associated with the variability involved in the combined board cracking determinations. This was not analyzed in detail because of cost and time limitations but it was observed that there often was considerable variation from scoreline-to-scoreline within a given sample. Another portion of the error may be related to the shear modulus determinations. The beam technique used herein suffers from the disadvantage that a relatively small effect must be distinguished from measurements at a few span lengths. Therefore, the shear modulus values are subject to considerable variability. A direct shear measurement method — preferably giving the shear stress-strain curve to failure — may be helpful in improving the predictions.

Also, it appears that a better theoretical understanding of the stresses involved in folding is needed in order to specify the properties needed. As mentioned previously, there are reasons to believe that stretch should be one of the more important properties involved. However, neither the conventional stretch values nor the special measurements on "felt side" specimens employed in this study were well related to cracking. The conventional stretch measurement is an average over a relatively long gage length; however, unpublished experiments on sack papers have shown that appreciable local variations in stretch occur from location-to-location along the length of tensile specimens. Cracking essentially involved the stretch over a relatively short length and may be more dependent on the local value than the average obtained in the conventional test. Schroeder (7), in discussing the forming of sheet metals indicated that greater strains may be found in the outer fibers of a bend than would be expected on the basis of the uniform strain in the tension test. This result is attributed to stress gradient effects. Thus, the more severely strained outer fibers are linked to less severely strained fibers nearer the neutral axis. The latter fibers probably lend stability to the outer fibers and, hence, make possible strains greater than the uniform strains in tension. He also comments that a useful criterion for formability "has been found to be the strain at fracture of a short length." Thus, it may be speculated that stretch measurements on relatively short tensile specimens would be better related to cracking than the conventional measurement over a long span. This could be investigated at relatively low cost using the samples on hand.

It would be desirable to determine the magnitude of the strain induced in the outer fiber layer of the double-face liner during folding. It is believed this could be accomplished experimentally by employing short gage length graphite strain gages applied to the double-face liner before folding. This type of gage is applied by a spray technique and unpublished work has shown that they can provide accurate strain measurements without the reinforcements effects encountered when conventional strain gages are cemented to paper. The strain measurements would show how the maximum strain levels which cause cracking vary with material properties, RH at time of folding, and scoring conditions.

Material variability probably deserves further consideration because the degree of cracking obtained under given conditions is dependent on both the variability in the folding process and material quality. If two linerboards had the same average property levels but one was appreciably more variable than the other, it might be anticipated that the more variable sample would exhibit more cracking under given conditions than the other. For example, the tensile properties of linerboard often exhibit considerable variation and this matter was not taken into consideration herein because of time and cost limitations. Analysis of the variability in the tensile stiffness and stretch results in relation to cracking might be helpful, particularly in conjunction with strain measurements during folding since the latter would provide estimates of the strain variations from location-to-location.

Attention has been centered on the tensile properties because of the high tensile stresses induced in the outer fiber layers. However, the inside fiber layers of the double-face liner are subjected to compressive stresses. The compressive strength of linerboard is much less than in tension; hence, the inner fiber layers may fail in compression before the outer fiber layers rupture. The compressive failure would shift the neutral axis toward the outside and alter the tensile stresses in the outer fiber layers. Viewed in this way, the compressive stress-strain properties may require consideration along with the tensile properties. In addition, the tensile stiffness of the linerboard probably should be evaluated at high stress levels near failure — i.e., in the inelastic region of the stress-strain curve.

LITERATURE CITED

1. Laurson, P. G., and Cox, W. J. Mechanics of materials. 2nd ed. New York, J. Wiley and Sons, Inc., 1947.

2. Timoshenko, S., and Young, D. H. Elements of strength of materials. 4th ed, Princeton, New Jersey, D. Van Nostrand Co., Inc., 1962.

3. Roark, R. J. Formulas for stress and strain. 4th ed. New York, McGraw Hill Book Co., 1965.

4. Jones, A. R., Tappi 51(5):203(May, 1968).

5. Setterholm, V. C., Benson, R., and Kuenzi, E. W., Tappi 51(5):196-202(May, 1968).

6. Project 1108-29. An investigation of linerboard cracking. Summary Report to FKI, Dec. 22, 1966.

7. Schroeder, W. ASTM Special Tech. Publication No. 107, 1950.

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APPENDIX I

TABLE IX

SIMPLE CORRELATION RESULTS BY GRADE WEIGHT AND RH

	Property	Correlation Coefficient: Linear, 69-lb Liners, 15% RH	Linear, 69-lb Liners, 50% RH	Linear, 90-lb Liners, 15% RH	Linear, 90-lb Liners, 50% RH	Probability, 69-lb Liners, 15% RH	Probability, 69-lb Liners, 50% RH	Probability, 90-lb Liners, 15% RH	Probability, 90-lb Liners, 50% RH
1	Tensile properties (whole sheet)								
	a. Tensile strength (T)	0.30	0.52	0.56[b]	0.69[a]	0.34	0.46	0.63[a]	0.68[a]
	b. Stretch (S)	0.04	0.10	0.21	0.10	-0.04	-0.07	0.37	0.16
	c. Tensile stiffness ($E_x t$)	0.20	0.38	-0.44	0.72[a]	0.32	0.36	0.39	0.71[a]
	d. TEA	0.14	0.30	0.35	0.32	0.08	0.09	0.48	0.37
2	Caliper (t)	0.01	-0.44	-0.22	-0.16	-0.12	-0.29	-0.17	-0.14
3	Apparent density	-0.10	0.37	0.58[b]	0.40	0.04	0.22	0.55[b]	0.37
4	Plug shear	0.20	0.53	0.15	0.14	0.31	0.36	0.15	0.03
5	Shear stiffness ($G_{xz}t$)	0.57[b]	0.49	0.50	0.66[a]	0.60[b]	0.57[b]	0.68[a]	0.68[a]
6	Bending modulus ($E_x b$)	-0.39	0.06	0.19	0.01	-0.27	-0.11	0.04	-0.06
7	Flexural stiffness (EI)	-0.16	-0.32	0.02	-0.13	-0.22	-0.27	-0.07	-0.18
8	z-Direction tensile								
	a. Unflexed	0.14	0.03	0.51	0.52[b]	0.11	0.10	0.67[a]	-0.59[b]
	b. Flexed to 0.188-in. radius	0.18	0.04	0.50	0.44	0.15	0.08	0.66[a]	0.52[b]
	c. Flexed to 0.096-in. radius	0.02	-0.12	0.62[b]	0.17	-0.05	-0.09	0.61	0.23
9	$G_{xz}t/S$	0.58[b]	0.44	0.49	0.73[a]	0.65[a]	0.58[b]	0.63[a]	0.73[a]
10	$E_x t/S$	0.16	-0.02	0.44	0.52[b]	0.20	0.20	0.48	0.54[b]
11	$G_{xz}t/E_x t$	0.56[b]	0.49	0.42	0.53[b]	0.58[b]	0.56[b]	0.61[b]	0.57[b]
12	T/S	-0.16	-0.12	-0.01	-0.08	-0.08	-0.03	-0.17	-0.16
13	t/s	0.04	-0.18	-0.22	-0.12	0.07	0.01	-0.36	-0.15

[a] Significant at the 0.05 level.

[b] Significant at the 0.10 level.